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GLOBAL OBSERVING SYSTEM SIMULATION EXPERIMENTS OF THE IONOSPHERE, THERMOSPHERE AND PLASMASPHERE

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14. ABSTRACT
The overall goal of this project was to set up a simulation framework and testbed for ionosphere-thermosphere (IT) data assimilation that could be used to investigate: a) the impact of sensor systems upon the performance of data assimilation algorithms; b) the impact of improvements in data assimilative algorithms upon the performance of those data assimilative algorithms; c) the impact of different choices of inputs to data assimilative models and other configuration choices upon the performance of data assimilation algorithms.

New ground and satellite data systems are constantly being proposed with different spatial-temporal configurations, and it is not clear what will maximize the impact on data assimilation performance. In particular, for this project, where the performance is quantized in terms of applications of interest to the Air Force, the metrics used to assess performance are applied systems metrics.

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1. Introduction

The overall goal of this project was to set up a simulation framework and testbed for ionosphere-thermosphere (IT) data assimilation that could be used to investigate:

a) The impact of sensor systems – particularly satellite sensor constellation systems – upon the performance of data assimilation algorithms;
b) The impact of improvements in data assimilative algorithms and/or methods upon the performance of those data assimilative algorithms;
c) The impact of different choices of inputs to data assimilative models (such as physics model, grid size, etc.) and other configuration choices upon the performance of data assimilation algorithms.

This is a useful concept, because new ground and satellite data systems are constantly being proposed with different spatial-temporal configurations, and it is not clear what will maximize the impact on data assimilation performance. In particular, for this project, where the performance is quantized in terms of applications of interest to the Air Force, the metrics used to assess performance are applied systems metrics. The impact on these metrics can be quite different from more basic science metrics, which could then lead to a different set of satellite and/or ground instrumentation to optimize performance.

2. Motivation

There are three primary motivations to this work. First, to develop a long-term simulation test bed that could be used to study data assimilation scenarios now and in the future. Second, to study the effect of adding satellite data sources – particularly RO occultations upon ionospheric data assimilation accuracy, and third, to understand the effects and limitations of the data assimilation algorithms IDA4D and EMPIRE and how they can be improved.

3. Description of Approach

The approach developed in this work is as follows:

1. Develop a simulation scenario
2. From the simulation scenario simulate the observations
3. Ingest the observations into the data assimilation algorithms IDA4D and EMPIRE
4. From the output of IDA4D and EMPIRE compute the state variables as well as any derived quantities used for applied comparisons
5. Compute metrics by comparing the data assimilative estimates to the underlying "truth" ionosphere-thermosphere
6. Document

Each of these steps in the approach is now described in more detail.

3.1. Simulation Scenario

A simulation scenario consists of a “truth” ionosphere-thermosphere simulation of state variables, and a configuration of both ground and space-based instruments.

3.1.1. Truth Ionosphere-Thermosphere Simulation

The truth simulation begins with a background model, either a first principles model or empirical model. Currently, the first principal model TIEGCM and the empirical model IRI are available for the background simulation. Both TIEGCM and IRI are publicly available codes, written in Fortran and compiled and operating at JHUAPL

Once the background, and admittedly smooth IT state has been simulated the option exists to add smaller scale structuring on top of the smooth IT state. Currently there are three options to add structure to the background state:

1. Gaussian depletion/enhancement regions: IDL code has been available for a number of years, written by Dr. Bust, that allows one to super-impose a very general region of enhancement or depletion upon a background electron density field. The user can choose the location of the center of the region, whether it is drifting with a constant three-dimensional velocity, a starting time, and “growth time”, and ending time and “decay time”, and the size of the region in latitude, longitude and altitude. Thus, the structures are very general, and can be used to test such things as resolution limits, the ability to capture motion and limits to sensitivity of variability. As many of these structures as desired can be added to the background density field.
2. Traveling Ionospheric Disturbances (TIDS): IDL code has been developed by Dr. Bust to super-impose wavelike variations on top of the background electron density field. This wavelike variation is based on Hooke’s analysis [Hooke, 1968] of the electron density response to a gravity wave. Thus it is a fully 3D density perturbation that moves in time, and has a altitude shape consistent with both the fact that gravity wave amplitudes grow exponentially with altitude, while above the F-region peak, density decays exponentially with amplitude.
3. Recently, Dr. Bust modified the Gaussian depletion code to represent an equatorial depletion bubble. In this case, only depletions are allowed, and the bubble extends along the magnetic field on both sides of the equator.

Once these smaller scale structures have been added to the background “truth” ionosphere, we are ready to define an instrument configuration.

3.1.2. Instrument Configuration

An instrument configuration consists of a number of different sets of instrument description. The type of description depends on whether it is ground or space based.

Ground Based: For ground-based information the following descriptions are necessary:

- Observation measured (TEC, 6300 Optical, etc.)
- The number of the instruments
- The location for each of the instruments (latitude, longitude, altitude)
- Systematic and random errors of the instrument if known; sensitivity, dynamic range, maximum and minimum sampling times etc.

- Instrument specific information such as field of view, resolution, limitations in angular view, all things that define what can be simulated with the instrument

Space Based: Space based (satellite based) instrumentation includes all the above for ground based, except for location, since that is not fixed. In addition, there are satellite specific items needed

- Satellite orbital information (if there are several instruments (homogeneous constellation) then orbital information for each satellite in the constellation)
- Satellite specific information about the instrument – look directions, scan or spin rates etc.

For some instrumentation the relationship between the observable and the underlying IT simulated state is complex and or non-linear (ionosonde time-delay versus frequency or optically thick paths for radiances). In those cases, a forward model relating the observable to the IT state must be available for proper simulation. In some cases, it is acceptable to simply simulate the output state after processing. For example for days side electron densities from EUF, it is possible to simply simulate the F-region parameters at the tangent altitudes, since often that is what is provided to the assimilative models.

3.2. Simulation of Observations

The instrument configuration described above is still somewhat vague. While the number of instruments, types, locations (for Ground) and orbits (for space) have been determined, details regarding data rates, spin or scan rates, types of observables (for multi-instrument observables such as ISRs) and other specific observation configurations are left to be determined for a specific simulation set. Here, for example, one can decide to collect downward 1356-Angstrom radiances at a certain cadence, and with a certain field of view.

Once the details of the instrument observables have been defined, the simulation scenario generated in 3.1 can be used to simulate observed data sets. The final step in preparing the observed data sets is to add systematic and/or random errors to the observables. These data sets are saved in file-formats that are the exact same as used by IDA4D and EMPIRE for real actual data sets. It should be noted, that this last step, the actual saved file-format is the only part of the entire process that is specific to IDA4D-EMPIRE.

3.3. Run IDA4D / EMPIRE on Simulated Observations

We now have simulated data for a specific configuration of ground and space instrumentation. IDA4D and possibly EMPIRE can then be run for several hours of time. Depending on whether the experiment is to evaluate the simulation scenario or whether it is to test out possible algorithm improvement to IDA4D/EMPIRE many different runs maybe undertaken with a change of input parameters for the same data configuration.

On the other hand, one might have a configuration with a constellation of 24 satellites, and then ask how much degradation in performance does one get for fewer satellites in the constellation. For this case several runs are made with the same overall simulation scenario but with different distributions.

The output of these runs will consist of a time series of 3D estimates of IT state variables, most notably, and estimated covariances on those state variables. For the case of IDA4D only, the only state variable estimated is electron density. If EMPIRE is also used, ion drifts, neutral winds and neutral composition can also be estimated.

3.4. Metric Analysis of IDA4D / EMPIRE State Variables

The final step is to determine how well the output state variables, and derived products obtained from the output variables (such as HF propagation parameters) compare with the simulated "truth" IT state variables and derived products. Depending on the problem being investigated, different sets of metrics will be selected and analyzed.

3.5. Documentation

All simulation scenarios, results and analysis are documented in a simulation results document.

4. Simulation Experiments

Once all the algorithms and numerical codes were developed, two separate simulation experiments were undertaken for this project. The first experiment the "Geoscan" experiment asked the simple question "how well can 66 satellites in LEO orbits, with GPS occultation receivers on each one recover the 3D time-evolving electron density distribution?"

The second experiment was a "mesoscale structure" experiment where we simulated mesoscale structure on top of a TIEGCM simulation, and investigated how different numbers of Geoscan type LEO orbits with radio occultations.

4.1. Geoscan

The Geoscan experiment was designed to investigate to what degree and accuracy the Geoscan constellation of 66 satellites, each with a GPS occultation receiver, could recover the global three-dimensional time-evolving electron density field.

To accomplish this, the first principle model of the ionosphere-thermosphere: the Thermosphere Ionosphere Electro-dynamic General Circulation Model (TIEGCM) was use to simulate the November 20, 2003 super-storm. An outline of the simulation configuration is given below.

1. The satellite tool-kit (STK) program was used to simulate the orbits for one day of all 66 Iridium Satellites.
2. TIEGCM was used to simulate the November 20, 2003 storm over a 3-hour period from 15-18 UT, which include the period where the storm enhanced density (SED) feature emerged over the USA sector. Samples were output every 15 minutes.
3. The actual GPS ephemeris for the GPS satellites for the November 20 2003 case was used to simulate the links between the RO receivers on the Iridium constellation and the GPS satellites. The Iridium orbit links were calculated to the GPS satellites, and only cases where the elevation angles to the GPS were negative (occultations) and the tangent altitude of the link was > 80km were used in the simulation.

4. In addition, as a baseline case, ground-based GPS TEC was simulated from the actual available global distribution of ground GPS stations. The actual existing links in the ground data are used for the simulations, meaning that various lines of sight used are the actual ones used for the real ground GPS observations for the day.
5. IDA4D Inversions
    - IDA4D used the empirical model IRI as background model rather than TIEGCM to ensure that IDA4D has no pre-knowledge of the TIEGCM truth simulation. That is we do NOT want to do the identical twin experiment, since it does not fairly evaluate the capabilities of data assimilation methods, nor the importance of the observations being studied.
    - Radio Occultation only case: For this case, no ground GPS or any other kind of simulated data is used beyond the RO simulated data from the Iridium constellation. This allows investigation of how well the Iridium RO only can recover the ionospheric electron density.
    - Ground GPS only case: Do another run using only the actual ground GPS TEC available for that day as a comparison. This allows us to compare how well ground GPS TEC can reproduce the electron density versus the Iridium RO data.

4.2. COSMIC-2 Mesoscale Structuring

This experiment was designed to study how well a constellation of satellites in polar orbit with RO, are able to reconstruct smaller scale structuring, and inclination orbits similar to the proposed high inclination COSMIC-2 are able to reproduce ionospheric state variables. In particular we add smaller scale structure to a smooth background ionosphere and see how well the observations, when ingested into data assimilation, can reproduce the structures.

4.2.1. Ionospheric Simulations

The background ionosphere simulation came from TIEGCM. The day chosen was a storm day, October 25, 2011. The ionosphere was sampled every 15 minutes, for the entire day. Then up to 5 different types of Gaussian depletion/enhancements structures are added to the background ionosphere. The Gaussian structures used in this study, and their properties are given in table 1 below.

4.2.2. Data Simulations

- Ground GPS TEC: Approximately 600 ground stations were selected from actual stations available for this day. Stations were selected such that none of the stations were closer than 100 km to each other. As in the Geoscan simulation, the actual GPS link geometry was use to generate the simulated TEC.
- COSMIC-2 Radio Occultations: Up to 24 polar orbit satellites were simulated, so that different combinations of number of satellites in the constellation can be investigated.
- The data were simulated for various configurations of the 5 Gaussian depletion structures defined above in table 1.

4.2.3. IDA4D runs

- The 600 simulated ground GPS stations were used along with 0, 5, 10, 24 RO occultation TEC. For each configuration of ground GPS and RO, and set of

Gaussian structures, IDA4D was run for two hours with 5 minute temporal updates.

Table 1: Gaussian Structures for this Study

Variables	GD 1	GD 2	GD 3	GD 4	GD 5
Lat0 (deg)	45 degrees	35	15	25	-35
Lon0 (deg)	270	290	90	180	250
Alt0 (km)	300	400	250	350	350
Sig_lat (deg)	5	2	2	15	5
Sig_lon(deg)	5	10	10	5	5
Sig_alt (km)	100	100	200	50	250
Vlat (m/s)	0.0	0.0	100	0	500
Vlon (m/s)	0.0	-100	300	500	0
Valt (m/s)	0.0	0	0	0	0
Start Time	N/A	N/A	14.5 UT	14.75	N/A
End Time	N/A	N/A	15.5 UT	N/A	N/A
Gth Rate(1/s)	0.0	0.0	.002	.002	0.0
Dec Rate(1/s)	0.0	0.0	.002	0.0	0.0

5. Results

Figure 1 presents the primary result from the Geoscan simulation. The upper left panel is the truth simulation at 18 UT, 3 hours into the simulation run. This is the TIEGCM prediction of what the vertical TEC (VTEC) is at 18 UT in the US sector for the super-storm of November 20, 2003. The top right panel, is the IRI simulation that was used as the initial background model in IDA4D. The IRI VTEC is very different from the truth simulation. The overall densities are lower, there is much less density in the US Sector, and the overall global ionosphere is more confined to the equatorial region and spread out over a larger range of longitudes and local time. The lower left panel shows the IDA4D reconstruction, starting with the IRI model in the upper right, and using only ground GPS TEC observations. IDA4D ran for 3 hours with 15-minute updates. One can tell that the ground GPS TEC data does improve the result. The overall density is higher in the center of the image, closer to the truth. The lower right panel is the IDA4D reconstruction with the radio occultation from all 66 Iridium satellites. The IDA4D reconstruction reproduces the truth ionosphere very accurately, both in terms of the spatial structuring (including the small tongue of ionization) and intensity of overall VTEC. What this demonstrates is that a constellation such as what was proposed in Geoscan would provide sufficient observations to data assimilative algorithms as to be able to accurately reproduce the large-scale global ionosphere.

Figures 2 and 3 present the primary results from the COSMIC-2 simulation. Figure 2 shows the truth simulation. The simulation consists of a background model simulation from TIEGCM on October 25, 2011, and then the two first Gaussian depletions in table 1 are added to the background simulation. The first Gaussian depletion is centered at 45 degrees latitude, 270 degrees longitude, and 300 km altitude, and is an enhancement that does not move or decay. It can be clearly seen in the top left panel of figure 2 at the starting time of 14 UT. As time goes on (other panels) it is clear the enhancement becomes less distinct as local noon approaches, and the background density increases. This illustrates that there is a time dependency on even static mesoscale structures, which has to be taken into account. The second Gaussian is centered at 35 degrees latitude and 290 degrees longitude. It is stretched in longitude, and moves towards the west at 100 m/s. While it is hard to see, because of the increased density coming from the southeast as local noon approaches, but the second depletion can be seen to be slowly drifting to the west as time goes on. Figure 3 shows several IDA4D reconstructions for the truth simulation at 15 UT. The top left panel shows the truth simulation at 15 UT. The top right panel shows the IDA4D inversion using only ground GPS TEC, the lower left panel shows the inversion after adding observations from RO on 5 satellites, while the lower right panel shows the inversion after 24 satellites are added to the ground GPS TEC. What is interesting, is while the reconstructions get more accurate with the additional satellite occultation data, it does not recover the mesoscale structures exactly. Unfortunately, it was outside the scope of this project to investigate how many satellites are required to accurately reproduce the mesoscale structuring.

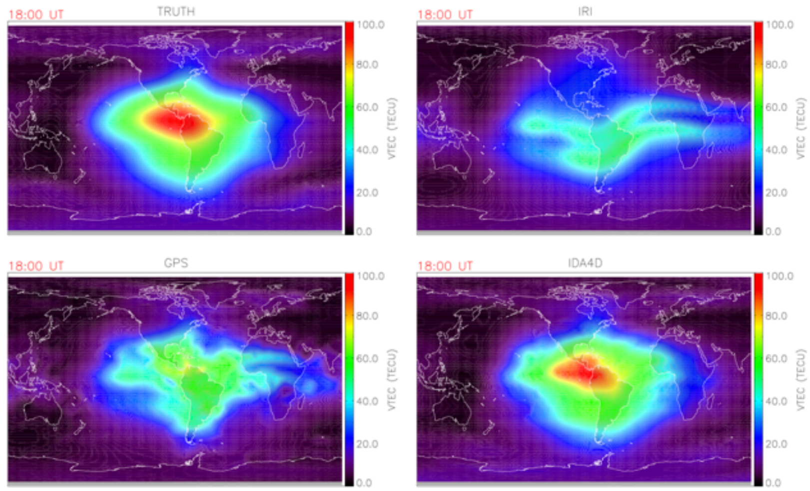

Figure 1: Comparison of "true" simulation ionosphere (top left), IRI background used to initialize IDA4D (top right), ground GS IDA4D reconstruction (bottom left) and Iridium RO IDA4D reconstruction (bottom right).

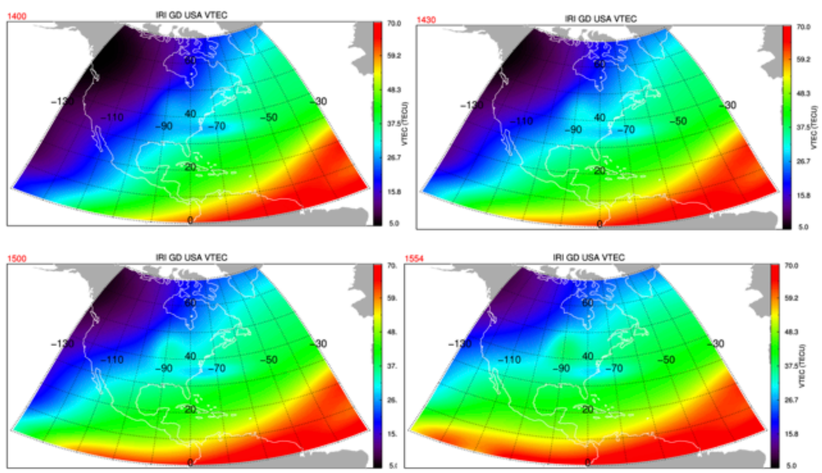

Figure 2: Gauss Depletion/Enhancement Plots: "Truth" simulations with Gaussian depletions GD1 and GD2 (from Table 1). Times at 14:00, 14:30, 15:00, 15:54 UT, gong from top left to lower right.

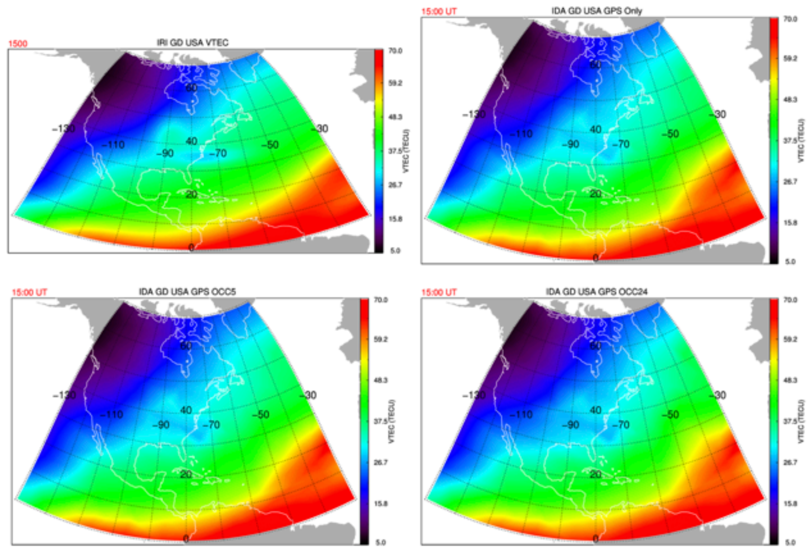

Figure 3: Gauss Depletion/Enhancement Plots: "IDA4D" reconstruction of "truth" simulation at 15:00 UT (upper left panel). Upper right panel is the IDA4D inversion with ground GPS only, lower left panel is IDA4D inversion with ground GPS and 5 RO satellites, and lower right panel is IDA4D inversion with ground GPS and 24 RO satellites.

6. Conclusions

This project has developed a permanent simulation testbed that can be used to investigate the effect of proposed observing systems upon the accuracy and resolution of data assimilation techniques. The simulation testbed can also be used to investigate new algorithms for data assimilation and see how well they improve the accuracy and resolution of the ionosphere-thermosphere. The simulation testbed consists of:

- The ability to simulate a background "true" ionosphere using a first principle ionospheric model or an empirical model.
- The ability to add several types of mesoscale structuring on top of the background ionospheric simulation
- The ability to simulate most data types that are ingested into data assimilative algorithms, including space and ground based TEC, measurements of electron density from ground and space, non-linear RF propagation, UV radiative recombination, and other similar observations
- The ability to simulate various types of instruments, digisondes, ISRs, as well as various satellite configurations.
- The ability to ingest the various data and observations into the data assimilation algorithms IDA4D and EMPIRE.
- The ability to analyze the results of the data assimilation in terms of metrics of performance

The testbed was used to simulate how accurately the Geoscan concept of 66 radio occultations on Iridium would be reconstruct the 3D time-evolving electron density field, and to simulate what scale of structures the proposed COSMIC-II high-inclination constellation of satellites would be able to accurately image.

Future work with the simulation testbed will include a investigating the accuracy and performance of a full coupled ionosphere-thermosphere data assimilation system under the influence of different observation data sets – including direct measurements of ion drifts, neutral winds and neutral composition. It is anticipated that this OSSE simulation testbed developed under this AFOSR grant, will be come a fundamental essential component of all future IT data assimilation and imaging that will take place at JHUAPL.